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GALAXY FORMATION FROM ANNIHILATION-GENERATED
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BIG-BANG COSMOLOGY
AND THE
 γ -RAY BACKGROUND SPECTRUM

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ABSTRACT:

Following the big-bang baryon symmetric cosmology of Omnes where an initial phase separation of matter and antimatter leads to regions of pure matter and pure antimatter containing masses of the size of galaxy clusters by a redshift which we calculate to be of the order of 500-600, we show that at these redshifts, annihilation pressure at the boundaries between the regions of matter and antimatter drives large scale supersonic turbulence which can trigger galaxy formation. This picture is consistent with the γ -ray background observations discussed previously by Stecker, Morgan, and Bredekamp. Gravitational binding of galaxies then occurs at a redshift of ~ 70 at which time vortical turbulent velocities of $\sim 3 \times 10^7$ cm/s lead to angular momenta for galaxies comparable with measured values.

INTRODUCTION:

In this paper, we will attempt to present a general scheme which we feel to be a plausible model for galaxy formation deserving of future study. This scheme draws upon and attempts to synthesize three basic concepts relating to big-bang cosmology and galaxy formation. These concepts are: (1) that galaxy formation may have been triggered by turbulence in the cosmic medium at an early stage in the evolution of the universe, (2) that the universe in its early stages was an emulsion of regions containing essentially pure matter and pure antimatter, and (3) that the observed background flux of cosmic gamma-radiation can be explained as due to matter-antimatter annihilation taking place on the boundaries of these regions with the observations providing a measure of the annihilation rate having occurred in the distant past. The first concept was examined by von Weizsäcker (1951) and gained further importance when Gamow pointed out that large density fluctuations like those produced by turbulence were needed to trigger galaxy formation in an expanding universe. Gamow (1954) then further developed this argument and also pointed out that fossilized turbulence could account for the nonuniform spatial distribution of galaxies. Oort further pointed out that a large scale turbulent eddy might bring matter together in a manner that would result in associations of galaxies in systems with a positive total energy (Oort 1969). Further contributions to theories of cosmological turbulence were made by Narai (1965a,b), Ozernoi and Chernin (1968), Sato, et al. (1970), Peebles (1970), Ozernoi and Chibisov (1970) and Harrison (1970a,b,1971). In all of these previous discussions, the initial turbulence had to be introduced in an ad hoc manner; we will show here a natural way of feeding turbulent energy into the cosmic medium as a result of antimatter annihilations following concept (2).

The second concept was suggested by Harrison (1967) to reconcile big-bang cosmology with the principle of baryon symmetry, but was introduced by him as an ad hoc initial condition. However, it was later reintroduced by Omnès in a much more satisfactory manner (Omnès 1969). Omnès suggested on the basis of strong-

interaction theory, that if we examine the big-bang model in its very early high-density state (corresponding to a critical temperature of ~ 350 MeV) a two-component phase separation could occur between matter and antimatter on a macroscopic scale. In subsequent papers (Omnès .1970,1971a,b). he traced the subsequent evolution and growth of the suggested matter-antimatter emulsion and showed that regions of pure matter and pure antimatter in the picture could grow to the size of galaxies or clusters of galaxies.

The third concept was examined by Stecker, et al. (1971) with the Harrison-Omnès picture in mind. They showed that such cosmological models could lead to the production of a background spectrum of cosmic gamma-radiation having the same features which seem to be present in the observed spectrum.

We will attempt to show here that the Omnès model which leads to annihilation rates of the order of those compatible with the gamma-ray observations also leads to annihilation pressures (at an earlier stage) which are sufficient to produce large scale turbulence with a maximum eddy size of the order of galaxy clusters. We then apply the general formulation of Ozernoi and his collaborators (but replacing his ad hoc "photon-eddy" hypothesis by annihilation-generated turbulence) to show how annihilation-generated turbulence can trigger galaxy formation and lead to angular momenta for galaxies comparable with measured values.

II: THE OMNES MODEL:

Omnes, following Gamow (1948a,b), considers a big-bang model which is initially at a very high temperature and density ($T \propto R^{-1}$ where T is the cosmic temperature and R is the geometric scale factor of the universe). Bosons and fermion pairs exist in statistical equilibrium with photons of the blackbody radiation field at a temperature $T \sim Mc^2/k$ where M is the rest-mass of the boson or fermion considered. Clearly, at a high enough temperature, the number of baryon-antibaryon pairs in the universe is of the same order as the number of photons in thermal equilibrium. However, at present ($T \approx 2.7$ K), the number of baryons is a small fraction of the number of photons

$$\eta \equiv N_B/N_\gamma \approx 10^{-10} - 10^{-8}$$

but this fraction is still much larger than that which would remain in thermal equilibrium in a blackbody at 2.7K (Chiu 1966). In fact, the ratio $\eta = 10^{-8}$ is reached in a blackbody at $T \approx 30$ MeV. The two possible ways to account for this discrepancy are 1) That there was initially a small excess of baryons of the order of 10^{-8} of the antibaryon number. 2) That the universe is baryon-symmetric and that a separation of matter from antimatter occurred at $T > 30$ MeV. A consistent theory leading to the fulfillment of the second hypothesis based on particle physics and statistical arguments has been given by Omnes (1969) and further refined by Aldrovandi and Caser (1971). In this model, various mesons are assumed to be bound states of the $N-\bar{N}$ system with the appropriate quantum numbers. In a "lattice gas" model then, a nucleon and an antinucleon when placed within a cell of size $r \sim 1$ fermi, look like a meson. However, the total number of meson is determined by statistical equilibrium at temperature T so that in a statistical average nucleons and antinucleons are excluded from occupying the same cell together. No such statistical exclusion principle applies to like baryons. Such a gas is similar to the model presented by Widom and Rowlinson (1970) for the study of liquid-vapor phase transitions. Their model is thermodynamically equivalent to a two-component system in which the pair-potential between molecules of like species is zero while that between unlike species implies a mutually excluded

volume $\sim r^3$. In such a model, Ruelle (1971) has rigorously shown the existence of a phase separation between the like and unlike species. At a stage when the baryonic density of the universe $n_B \sim r^{-3}$ or more (corresponding in Omnès' terminology to $T \geq T_c$) this phase separation can then be expected to take place*. Daschen, et al. (1969) have generalized the formalism originally given by Beth and Uhlenbeck (1937) to express the second virial expansion coefficient of the free energy of a system of strongly interacting particles in terms of observed scattering phase shifts. Omnès (1970) applied this treatment in his original work to show that above a critical density, the free energy of a gas of nucleons and antinucleons is a minimum for a phase of separately existing components containing excesses of nucleons and antinucleons respectively. The work of Ruelle proves that such a phase separation will indeed occur.

Following the epoch in the expansion of the universe when the density drops below the critical value ($T < T_c$), the two phases become unstable and matter and antimatter tend to mix and annihilate. Nevertheless, this process is slowed down by the strong pressure produced by annihilation at the boundary between regions of opposite baryonic number (the Leidenfrost effect pointed out by Alfvén and Klein (1962)). During this annihilation period, the characteristic size of the regions of excess baryons and excess antibaryons in the emulsion is roughly equal to the diffusion length of the baryons. Omnès defines the end of the "annihilation period as corresponding to the time when the radiation temperature drops to ~ 30 keV. At this point enough of the electron-positron pairs in the blackbody radiation have annihilated so that the mean-free-path of high energy γ -rays (produced by the

* This statistical argument, which is different from the one given by Omnès in the references, was pointed out by him to one of us in a private discussion.

decay of π^0 -mesons arising from baryon-antibaryon annihilation) increases to the size of an average emulsion cell. At this point then, the annihilation pressure gradient extends over the whole cell and momentum can be transmitted on macroscopic scales of the order of the cell size to the fluid as a whole. Velocities can then be induced as large as

$$v_{\max} \sim (nM_p c^2 / \epsilon) v_t \quad (1)$$

where n is the baryon density, ϵ is the blackbody radiation density and v_t is the thermal velocity of the baryons in temperature equilibrium with the blackbody radiation (Omnes 1971c).

From this point on, in what Omnes defines as the coalescence period (Omnes 1971b), the characteristic size of the emulsion regions, d , grows in a way such that

$$d \geq \lambda_\gamma \quad (2)$$

where λ_γ is the mean free path of the pion-decay γ -rays. Equation (2) holds until the point when the radiation energy density (ϵ) drops to the value equal to that of the matter energy density ($nM_p c^2$) (Note: $\epsilon \propto t^{-8/3}$ and $n \propto t^{-2}$ at this time, where t is the time after the initial big-bang). This corresponds to a time $\sim 1.5 \times 10^4$ yr. after the big-bang when the corresponding blackbody temperature was $\sim 3.2 \times 10^4$ K (see Appendix 1 for cosmological relations). The important relation giving the size of the emulsion regions of matter and antimatter as a function of blackbody temperature is shown in Figure 1. For further details of the Omnes cosmological model, we refer the reader to the papers by Omnes listed in the references.

III: THE PLASMA PERIOD ($\sim 5 \times 10^2 \leq z \leq \sim 10^4$)

We begin our original discussion of galaxy formation where Omnès' coalescence model stops, i.e., $\sim 1.5 \times 10^4$ yr after the "big-bang" at a redshift $z_{eq} \simeq 1.2 \times 10^4$ when the matter density ρ is equal to the radiation density ϵ . The following period ($\sim 5 \times 10^2 \leq z \leq \sim 10^4$) when $\rho > \epsilon$, but when the cosmic matter is still in the plasma state, we designate the plasma period (see appendices 1 and 2).

The study of annihilation on a boundary region in appendix 2, shows that in a macroscopic collision of matter and antimatter regions with velocity v_{f1} , the matter contained within a layer of thickness λ_X from the boundary will move away from the boundary with a velocity

$$v_{f2} \simeq (2Fcv_{f1})^{\frac{1}{3}} \quad (3)$$

where F is the dynamic efficiency factor given by equations (A2-30) and (A2-31). It follows from equations (A2-30), (A2-31), and (3) that if we consider an initial estimate of v_{f1} to be roughly given by equation (1) for the end of the radiation period ($z=z_{eq}$) so that $v_{f1} \sim v_t \simeq 2 \times 10^6$ cm/s, $v_{f2} > v_{f1}$ and the collision is superelastic. Referring to appendix 2, if the total mass of plasma, M_t , in a fluid cell involved in a collision is larger than M_λ , the mass of the cell within a distance λ_X of the boundary, v_{f2} will in general be less than the value given by equation (3). The average fluid velocity will increase in boundary collisions only if

$$d/\lambda_X < v_{f2}/v_{f1} \quad (4)$$

estimated by a simple plane geometry model.

When the plasma moves with a random fluid velocity $v_f \geq v_{exp} \sim d/t$ where v_{exp} is the cosmological expansion velocity, the average coalescence growth rate for emulsion regions (dd/dt) $\sim v_f$ because matter-antimatter

collisions are elastic or superelastic and matter-matter collisions are inelastic. Thus, at a time $t(z)$, the characteristic emulsion size is of the order

$$d(z) \sim v_f(z)t(z) \quad (5)$$

where $t(z)$ is given by (A1-7).

At the beginning of the plasma period, the annihilation rate must be at least equal to the value given by the diffusion process and this value for Ψ_s is given by equation (A2-7). The average annihilation rate per unit volume is then

$$\Psi_v \sim \Psi_s/d \quad (6)$$

Combining (6) and (A2-7) we find

$$\Psi_v \approx 0.37 N_0 v_t/d \quad (7)$$

At $z = z_{eq}$, v_{max} as given by equation (1) is smaller than $d\lambda_Y/dt$ (the coalescence growth rate during the radiation period as given by Omnès) by almost a factor of 30, but the contributions of the Omnès coalescence process and the collision process (appendix 2) in producing macroscopic motions must at least be of the same order so that

$$d(z - z_{eq}) \geq 2 \lambda_X \quad (8)$$

The value of N_0 in equation (7) is $\sim n/20$ (Omnès 1971b) so that the lower limit on Ψ_v given by pure diffusion is

$$\Psi_{v,d} \approx 3.3 \times 10^{-34} (1+z)^{6.5} \text{ cm}^{-3} \text{ s}^{-1} \quad (9)$$

for $z \sim z_{eq}$

The maximum dynamic fluid velocity produced by annihilation is given by

$$v_f = [(0.27 \cdot 2m_p c^2 \Psi_{v,d} Ft) / (\frac{1}{2} m_p n)]^{\frac{1}{2}} \quad (10)$$

$$\approx c (\Psi_{v,d} Ft/n)^{\frac{1}{2}}$$

so that for $z \sim z_{eq}$, $v_f \sim 2 \times 10^8$ cm/s. This value is much higher than v_t and we conclude that the annihilation rate Ψ_v will be determined by fluid motions rather than diffusion (at these redshifts) and $\Psi_v > \Psi_{v,d}$. At later stages of the plasma period, most of the annihilation results from fluid collisions with a velocity of the order of the average fluid velocity and we thus expect the minimum fluid velocity to be given by the relation (10). Using condition (4) together with equation (3) at $z \sim 600$ when $F \sim 1$, we find the upper limit for d at the end of the plasma period to be

$$d_{\max} \sim 10^{-20} \lambda_X \quad (11)$$

The corresponding fluid velocity as given by equation (5) is

$$v_{f,\max} \simeq 2.5 \times 10^{13} (1+z)^{-3/2} \text{ cm/s} \quad (12)$$

A minimum value for d at the end of the plasma period can be obtained from equations (5) and (10);

$$d_{\min} \simeq 2.3 \times 10^{25} (1+z)^{-11/8} \quad (13)$$

When d reaches the limit d_{\max} given by equation (11), v_f cannot be increased further so that by combining equations (10) and (12) we find for an upper limit on the annihilation rate at the end of the plasma period when $F \sim 1$

$$\Psi_{v,\max} \simeq 10^2 \Psi_{v,d} \quad \text{at } z \simeq z_n \sim 600 \quad (14)$$

At redshifts $< z_n$, the fluid velocity decays $\propto (1+z)$ because F is no longer increasing and Ψ_v decreases rapidly with z . The decay of the fluid velocity and the growth of $d \propto (1+z)^{-1}$ for $z < z_n$ are due to the cosmological expansion (Ozernoi and Chibisov 1970). The annihilation rate then

$$\Psi_v \propto n v_f (M_a/M_t) d^{-1} \quad (15)$$

From (A2-19) and (A2-20), it follows that

$$4(v_f/c)^2 \leq (M_a/M_t) \leq 4(v_f/c) \quad (16)$$

so that we find from equations (14) and (15)

$$\Psi_v \propto (1+z)^{6+\kappa} \quad \text{where } 0 \leq \kappa \leq 1. \quad (17)$$

The constant of proportionality is determined from equations (9) and (14) at $z \approx z_n$. The resultant values for v_f, d , and Ψ_v as a function of z are shown in figures 2, 3, and 4 respectively.

From the upper and lower limits on d , we find that at the end of the plasma period, the emulsion regions of pure matter and pure antimatter contain masses of the order of

$$\sim 10^{11} \leq (M/M_\odot) \leq \sim 6 \times 10^{14} \quad (18)$$

where $M_\odot \approx 2 \times 10^{33}$ g is equal to one solar mass.

Thus, even assuming that only 5-10 per cent of the total mass of the universe goes into galaxy formation as is consistent with the turbulence picture and the γ -ray results (see references in appendix 1), it appears likely that the emulsion regions will grow large enough by the end of the plasma period to contain masses of the size of galaxy clusters - particularly noting the uncertainty in d ($M \propto d^3$) and the fact that our estimate of d is an average emulsion size so that somewhat larger sizes can be expected to exist. Thus, in this picture, one would expect that all galaxies in a cluster would be of the same type, i.e., all matter or all antimatter.

IV: THE ONSET OF TURBULENCE AND GALAXY FORMATION

The size scale of the emulsion regions and the magnitude of the fluid velocities v_f estimated in the previous section to be induced by annihilation pressure are of sufficient size to result in large scale turbulence. Turbulence can be sustained if the Reynolds number of the cosmic fluid on a scale ℓ

$$R \equiv v_f \ell / \nu \quad (19)$$

is of the order of $10\text{-}10^2$ (Heisenberg 1947) where ν is the viscosity of the fluid.

During the plasma period, the plasma and blackbody radiation field are coupled and behave as a single fluid with the fluid viscosity determined by the radiation field. The coefficient of viscosity is then given by

$$\nu_r \equiv \frac{4}{15} \frac{c \epsilon m}{\sigma_T \rho (\rho + (4/3)\epsilon)} \quad (20)$$

(see, e.g., Silk 1971).

During the plasma period, $\epsilon \equiv \rho (1+z)/(1+z_{eq}) < \rho$ and

$$\nu_r \simeq \frac{4}{15} \frac{c}{\sigma_T n} (\epsilon/\rho) \simeq 10^{35} (1+z)^{-2} \text{ cm}^2 \text{ s}^{-1} \quad (21)$$

Using ν_r as given by equation (21) and the values for v_f and d estimated in the previous section to determine the value of the Reynolds number for the fluid, we find that turbulence on a scale $0.1d \leq \ell \leq d$ can set in during the plasma period for $\sim 5 \times 10^2 \leq z \leq 3 \times 10^3$. We thus would expect that large scale turbulence existed in the cosmic fluid by the end of the plasma period. During this period, the turbulence is subsonic with the velocity of sound in the fluid being determined by the radiation field to be of the order of 10^{10} cm/s (see appendix 3). During the plasma period then $v_f < u_{pl}$ and the plasma behaves as an incompressible fluid.

The Kolmogoroff law for incompressible isotropic turbulence has been well verified in the laboratory and has been nicely summarized by von Weizsäcker (1951) for astrophysical applications. We will briefly summarize here von Weizsäcker's discussion.

The energy density dissipated per unit density per unit time Γ through the effect of fluid viscosity is given by

$$\Gamma \approx \left| \nabla \times \mathbf{v}_T \right|^2 \quad (22)$$

where \mathbf{v}_T is the turbulent velocity of an eddy of the fluid.

An eddy of size ℓ has an effective eddy viscosity

$$\nu_\ell \approx \mathbf{v}_T \ell \quad (23)$$

From dimensional arguments, it follows that

$$\left| \nabla \times \mathbf{v}_T \right|^2 \approx \mathbf{v}_T^2 / \ell^2 \quad (24)$$

so that from equations (22) through (24), we find

$$\Gamma \approx \mathbf{v}_T^3 / \ell \quad (25)$$

Since, in equilibrium, the energy flow through eddies of all sizes ℓ must be a constant, it follows that

$$\mathbf{v}_T \propto \ell^{1/3} \quad (26)$$

and

$$\nu_\ell \approx \mathbf{v}_T \ell \propto \ell^{4/3} \quad (27)$$

The minimum eddy scale below which turbulence is rapidly dissipated by viscosity is that for which the Reynolds number is ~ 1 , so that from equations (19) and (25) we find

$$\ell_{\min} \approx (\mathbf{v}^3 / \Gamma)^{1/4} \quad (28)$$

The Kolmogoroff spectrum given by equation (26) is established for all eddy scales

$$\sim \ell_{\min} \leq \ell \leq \sim d \quad (29)$$

At the end of the plasma period ($z \approx z_n$) when neutralization occurs, the radiation field decouples from the matter and two drastic changes occur: (1) The viscosity of the fluid drops dramatically to the kinematic viscosity

$$\nu_k \approx 10^{-16} T^{5/2} \rho^{-1} \approx 3 \times 10^{14} (1+z)^{-\frac{1}{2}} \text{ cm}^2/\text{s} \quad (30)$$

(Spitzer 1962, Zel'dovich, et al. 1968). This drop in the viscosity results in a very large Reynolds number for the large scale fluid motions and extensive turbulence down to scales $\ell_{\min} \ll d$. (2) The velocity of sound in the fluid drops by about four orders of magnitude (see appendix 3) so that $v_f > u_n$ and the turbulence becomes supersonic. The fluid pressures resulting are then greater than the kinetic gas pressure and the fluid becomes compressible. Real shock waves of large dimensions cannot exist, however, because density fluctuations on the smaller eddy scales immediately divert the wave fronts into statistically distributed directions (von Weizsäcker 1951). The net result of the supersonic turbulence is to cause the large scale density fluctuations needed to trigger galaxy formation in an expanding universe (von Weizsäcker 1951, Gamow 1954, Ozernoi and Chibisov 1970).

At the end of the plasma period ($z \approx z_n$), as we showed in the previous section, the maximum fluid velocity on a scale d can be estimated to be

$$\sim 1.5 \times 10^8 \text{ cm/s} \leq v_{\max}(z_n) \leq \sim 1.5 \times 10^9 \text{ cm/s} \quad (31)$$

During the neutral period, $z < z_n$, Kolmogoroff's law for an incompressible fluid (equation (26)) must be modified to allow for compress-

ibility and becomes

$$v_T(\ell) = v_{\max} [\ell/d]^{\frac{1}{3} + \mu} \quad (32)$$

$$\text{where, experimentally} \quad 0 \leq \mu \leq \sim 0.12 \quad (33)$$

and a good estimate for μ under astrophysical conditions is

$$\mu \simeq 0.07 \quad (33)$$

(von Weizsäcker 1951).

The maximum turbulent velocity as a function of redshift will not decrease faster than $v \propto (1+z)$ (Ozernoi and Chibisov 1970). Thus

$$v_T(\ell, z) = C v_n \frac{1+z}{1+z_n} (L/D)^{0.4} \quad (35)$$

where $1 \leq C \leq \sim 10$ and $v_n \simeq 1.5 \times 10^8$ cm/s, and the comoving variables

$$\begin{aligned} L &\equiv \ell(1+z) \\ D &\equiv d(1+z) \end{aligned} \quad (36)$$

According to Ozernoi and Chibisov, gravitationally bound protoclouds can form when the virial theorem can be satisfied. The turbulent kinetic energy per gram decays $\propto (1+z)^2$ and the gravitational potential energy per gram scales as $\propto (1+z)$. Ozernoi and Chibisov show that $\langle 2T \rangle + \langle U \rangle \leq 0$ for $z \leq z_b$ where

$$(1+z_b) = \frac{2}{15} (1+z_n) \quad (37)$$

At that point, the maximum velocity

$$\sim 2 \times 10^7 \text{ cm/s} \leq v_{\max}(z_b) \leq \sim 2 \times 10^8 \text{ cm/s} \quad (38)$$

and the gas density $n(z_b) \simeq 1 \text{ cm}^{-3}$ so that 1 galactic mass is contained within a scale

$$\ell_g \simeq 3 \times 10^{22} \text{ cm} \quad (39)$$

for which the maximum rotational turbulent velocity from equation (35) is

$$\sim 2 \times 10^7 \text{ cm/s} \leq v_{\text{max}}(\ell_g) \leq \sim 6 \times 10^7 \text{ cm/s} \quad (40)$$

After $t(z_b)$, the protogalactic clouds maintain their integrity as indicated by the fact that for our galaxy

$$n_g \simeq n(z_b) \quad (41)$$

and the galactic radius

$$r_g \sim \ell_g \quad (42).$$

Further galactic evolution may follow along the lines suggested by von Weizsäcker (1951) but will not be examined here.

We also find observationally that galaxies have a maximum observed rotational velocity

$$v_{\text{rot,max}} \simeq 3 \times 10^7 \text{ cm/s} \quad (43)$$

(Brosche 1967) in agreement with equation (40).

V: THE γ -RAY BACKGROUND SPECTRUM:

The most direct empirical verification of the extension of the Omnes cosmology suggested here lies in a study of the cosmic γ -ray background spectrum above 1 MeV; those γ -rays being presumably the direct products of the decay of π^0 -mesons produced in proton-antiproton annihilations (Stecker, et al. 1971). Two characteristics of the spectrum have been determined by Stecker, et al.: (1) a flattening of the γ -ray spectrum in the neighborhood of 1 MeV due to absorption effects at $z \geq \sim 100$ and (2) a power-law form for the γ -ray spectrum at higher energies (~ 5 -50 MeV).

If we denote the unredshifted γ -ray spectrum from proton-antiproton annihilation by $f_A(E_\gamma)$, then the γ -ray spectrum predicted for an Einstein-de Sitter universe (see appendix 1) is given by

$$I_A(E_\gamma) \propto \int dz (1+z)^{-4.5} \Psi(z) f_A[E_\gamma(1+z)] \quad (44)$$

(Stecker 1971), where the integral is taken over redshifts where absorption is unimportant ($z \leq \sim 100$) so that equation (44) is only valid for $\sim 5 \leq E_\gamma \leq \sim 50$ MeV (Stecker, et al. 1971).

If we then represent $\Psi(z)$ in the form

$$\Psi(z) \propto (1+z)^{6+\kappa} \quad (45)$$

as suggested by equation (17), then

$$I_A(E_\gamma) \propto \int dz (1+z)^\alpha f_A[E_\gamma(1+z)] \quad (46)$$

where

$$\alpha \equiv 1.5 + \kappa$$

Then, because of the bounded form of $f_A(E_\gamma)$, the cosmological γ -ray spectrum between ~ 5 and ~ 50 MeV has the power-law form

$$\begin{aligned}
I_A(E_\gamma) dE_\gamma &\propto E_\gamma^{-(\alpha+1)} dE_\gamma \\
&\propto E_\gamma^{-(2.5+\kappa)} dE_\gamma
\end{aligned} \tag{47}$$

where $0 \leq \kappa \leq 1$

(Stecker 1971).

For the microscopic model discussed by Stecker, et al. (1971), the comparable value of κ was 0.36 ; the macroscopic model gives values for κ between 0 and 1. In the notation of this paper, the effective annihilation rate used by Stecker, et al. which was normalized to the γ -ray observations is (in $\text{cm}^{-3}\text{s}^{-1}$)

$$\Psi_\gamma = 0.8 \times 10^{-34} (1+z)^{6.36} \quad z \leq z_b \tag{48}$$

which, of course, is only valid for the lower redshifts $z \leq z_b$, where the universe is transparent to γ -radiation. An extrapolation of this function to higher redshifts leads to rotational velocities $\sim 10^7$ cm/s for our turbulence model which compares well with the observed value as given by equation (43). It is also within order of magnitude agreement with equation (9). Gravitational binding and subsequent strengthening of magnetic fields for $z \leq z_b$ may be expected to reduce the annihilation rate somewhat below the extrapolated value from higher redshifts.

We conclude that the γ -ray evidence as discussed by Stecker, et al. lends support to the picture presented here for galaxy formation by annihilation-generated turbulence. Other effects of the model presented here may be (1) some distortion of the 2.7 K blackbody spectrum on the high-frequency side, and (2) heating of the intergalactic medium by the decay of turbulence at low redshifts.

Appendix 1: Cosmological Relations Used in the Calculation.

We adapt here for the geometry of our cosmological model, the isotropic and homogeneous solution to the Einstein field equations given for the Robertson-Walker metric

$$ds^2 = c^2 dt^2 - R^2(t) du^2, \quad (\text{A1-1})$$

where $R(t)$ is the scale with which the universe expands as a function of time t after the big bang. If a photon is emitted at a time t , and received at a time t_0 , it can easily be shown that the relation between the amount the photon has been Doppler-shifted due to the expansion of the universe, $\Delta\lambda/\lambda \equiv z$, and the time of emission is given by

$$R_0/R(t) = 1 + z. \quad (\text{A1-2})$$

It then follows from (A1-2) that particle densities at time t scale with redshift z as follows:

$$n_p = n_{p,0} (1+z)^3, \quad n_\gamma = n_{\gamma,0} (1+z)^3. \quad (\text{A1-3})$$

Photon energies scale with redshift as the frequencies according to the Planck relation $E_\gamma = h\nu$ so that

$$E_\gamma = E_{\gamma,0} (1+z). \quad (\text{A1-4})$$

From (A1-3) and (A1-4), it can be shown that the temperature of the blackbody radiation scales with redshift as

$$T = T_0 (1+z) \quad (\text{A1-5})$$

where T_0 is observed to be 2.7 K. It follows from (A1-5) that the photon energy density $\epsilon_\gamma \propto T^4 \propto (1+z)^4$.

The homogeneous-isotropic solution to the Einstein field equations contains only two arbitrary constants which must be determined by observation (if, as here, we set the "cosmological constant" $\lambda = 0$); they are the Hubble constant, H_0 , and a parameter Ω which is proportional to the mean matter density in the universe.

We will choose here for the Hubble constant, the most recent value of $\sim 1.7 \times 10^{-18} \text{sec}^{-1}$ (Abell 1971). The parameter Ω is a measure of the deceleration of the universe due to gravitational effects and is defined as

$$\Omega \equiv n_0/n_c \quad (\text{A1-6})$$

where n_c is the mean density of matter needed to close the universe gravitationally. In this discussion, we will take $\Omega = 1$ in order to preserve consistency with the antimatter-annihilation explanation of the γ -ray observations (Stecker, et al. 1971) and with the turbulence hypothesis for galaxy formation (Oort 1969). This corresponds to the Einstein-de Sitter model (which, in any case, is valid for $\Omega z \gg 1$) which gives the time-redshift relation

$$t = t_0(1+z)^{-3/2} \quad (\text{A1-7})$$

where t_0 is the present age of the universe ($\sim 2 \times 10^{10} \text{yr}$).

A more complete discussion may be found in references such as McVittie (1965). Simplified derivations for application to γ -ray astronomy may be found in Stecker (1971).

Appendix 2: Annihilation of Matter and Antimatter in Boundary Regions.

A. Annihilation rate when the fluid velocity v_f is less than the thermal velocity v_t .

In this case, mixing of matter and antimatter by diffusion determines the mean annihilation rate. The equations for matter and antimatter density N_p and $N_{\bar{p}}$ as a function of distance x perpendicular to the boundary surface are

$$\begin{aligned} \frac{\partial N_p}{\partial t} &= - \langle \sigma_A v_t \rangle N_p N_{\bar{p}} + D \frac{\partial^2 N_p}{\partial x^2} + v_d \frac{\partial N_p}{\partial x} \\ \frac{\partial N_{\bar{p}}}{\partial t} &= - \langle \sigma_A v_t \rangle N_p N_{\bar{p}} + D \frac{\partial^2 N_{\bar{p}}}{\partial x^2} - v_d \frac{\partial N_{\bar{p}}}{\partial x} \end{aligned} \quad (\text{A2-1})$$

where σ_A is the cross-section for matter-antimatter annihilation, D is the effective diffusion coefficient and v_d is the effective diffusion velocity for matter and antimatter entering the annihilation region (Bessard, Dennefeld,

and Puget 1969). The stationary solutions of (A2-1) are given by

$$\begin{aligned} N_p &= N_0 \frac{e^{2x/h}}{4 \cosh^2(x/h)} \\ N_p^- &= N_0 \frac{e^{-2x/h}}{4 \cosh^2(x/h)} \end{aligned} \quad (\text{A2-2})$$

with the boundary conditions $N_p(\infty) \equiv N_p^-(\infty) \equiv N_0$ and $N_p(-\infty) = N_p^-(-\infty) = 0$ (Omnès 1971a). The characteristic dimension h , and the diffusion velocity v_d are given by

$$h = 2(6D/N_0 \langle \sigma_A v_t \rangle)^{\frac{1}{2}} \quad (\text{A2-3})$$

and

$$v_d = 2D/h.$$

The total annihilation rate per unit surface area is then

$$\Psi_S = \int_{-\infty}^{\infty} dx \langle \sigma_A v_t \rangle N_p N_p^- = \frac{\langle \sigma_A v_t \rangle N_0^2 h}{12}. \quad (\text{A2-4})$$

The diffusion coefficient is given by

$$D = \frac{1}{3} \lambda_A v_t \quad (\text{A2-5})$$

so that

$$h = 2\sqrt{2} \lambda_A \quad (\text{A2-6})$$

and

$$v_d \equiv v_t/3\sqrt{2}$$

where λ_A is the annihilation mean-free-path, equal to $(N\sigma_A)^{-1}$.

The resultant expression for Ψ_S then simplifies to

$$\Psi_S = 0.37 N_0 v_t \quad (\text{A2-7})$$

B. Annihilation rate when the fluid velocity v_f is greater than the thermal velocity v_t .

When $v_f > v_t$, macroscopic masses of matter and antimatter will collide as a result of the random fluid motions and the complicated geometry of the emul-

sion and considerably disrupt the stationary state just described. This situation occurs for $z < 4 \times 10^4$ (see figure 2). Let us consider such a collision beginning at time $t = 0$. For $t < \tau_A = (N\sigma_A v_f)^{-1}$, matter and antimatter mix on the boundary with a rate Nv_f per unit area. For times $t > \tau_A$, a strong flux of γ -rays and relativistic electrons is emitted at the boundary region. We consider here the energy carried by the electrons which have an average energy of ~ 100 MeV and neglect the effect of the γ -rays whose mean free-path is of the order of the emulsion size, d . The electrons lose their energy through Compton collisions with blackbody photons and produce X-rays with an average energy

$$\langle E_X \rangle = \frac{4\langle E_e \rangle^2}{3(m_e c^2)^2} (2.7kT) \approx 32(1+z) \text{ eV} \quad (\text{A2-8})$$

The lifetime of the electrons is then

$$\tau_e = (n_\gamma \sigma_T c)^{-1} (E_e / E_X) \approx 4 \times 10^{17} (1+z)^{-4} \text{ s} \quad (\text{A2-9})$$

where n_γ is the photon density of the blackbody radiation and σ_T is the Thompson cross section.

The X-rays in turn lose their energy through Compton collisions with electrons of the cosmic plasma and their mean-free-path is

$$\lambda_X = (n_p \sigma_T)^{-1} = 5 \times 10^{29} (1+z)^{-3} \text{ cm} . \quad (\text{A2-10})$$

In each collision, the X-rays lose an energy given roughly by

$$\Delta E_X \approx E_X^2 / m_e c^2 \approx 2 \times 10^{-3} (1+z)^2 \text{ eV} . \quad (\text{A2-11})$$

The time for transport of momentum from the X-rays to the plasma is

then

$$\tau_{\text{mom}} \approx \lambda_X / c \approx 1.7 \times 10^{19} (1+z)^{-3} \text{ s} \quad (\text{A2-12})$$

and the time for transport of energy is given by

$$\tau_E \approx (\lambda_X / c) (E_X / \Delta E_X) \approx 2.7 \times 10^{23} (1+z)^{-4} \text{ s} . \quad (\text{A2-13})$$

The average momentum transmitted per second during the burst of annihilation is

$$\frac{\Delta p}{\Delta t} = (n_p v_f / \lambda_X) (0.27 m_p c / n_p) \approx 0.27 m_p v_f c \lambda_X^{-1} \quad (\text{A2-14})$$

where the factor 0.27 is the fraction of annihilation energy transmitted to the electrons and positrons which are among the final products of the annihilation of the protons and antiprotons. The annihilation rate per unit area is $n v_f$ for times $t > \tau_A$ because $\tau_{\text{mom}} > \tau_A$ for most of the period we consider. The change in the velocity of a nonrelativistic electron due to electrostatic interactions with protons is given by

$$\Delta v_e = \frac{8\pi e^4 n}{m_e^2} (\ln \Lambda) v_t^{-2} G\left(\frac{v_e}{v_t}\right) \quad (\text{A2-15})$$

(Spitzer 1962) where v_e is the electron velocity, v_t is the thermal velocity of the protons, $\ln \Lambda$ and G are functions of v_e , v_t , and n . From (A2-14) and (A2-15) we see that the electrons and protons must have a relative velocity v_r given by the relation

$$\frac{0.27 v_f m_p c}{\lambda_X} = \frac{8\pi e^4 n}{m_e} (\ln \Lambda) v_t^{-2} G\left(\frac{v_e}{v_t}\right) \quad (\text{A2-16})$$

Equation (A2-16) gives $v_r \sim 10^5$ cm/s for $z \sim 10^4$. Such a relative velocity corresponds to a huge electric current and will rapidly lead to fields which will stop the relative motions of the electrons and protons and transmit the momentum of the electrons to the whole fluid. With such fields, $eE \approx \Delta p / \Delta t$ from equation (A2-14) and fluid motions with velocity v_f toward the boundary will stop in a time

$$\text{such that} \quad \epsilon E t = m_p v_f \quad (\text{A2-17})$$

which implies that

$$t = \lambda_X / 0.27 c \approx 4 \tau_{\text{mom}} \quad (\text{A2-18})$$

Thus, if we consider a mass of fluid moving with velocity v_f , it will be stopped by annihilation pressure at the boundary region in a time comparable to τ_{mom} within a distance λ_X of the boundary with the annihilated mass M_a such that the momentum produced is equal to the initial momentum of the gas. Denoting the total mass of the fluid within a distance λ_X by M_λ ,

$$0.27 M_a c = M_\lambda v_f. \quad (\text{A2-19})$$

For fluid motions involving total masses $M_t > M_\lambda$, one can still consider the mass of the fluid within λ_X and show that equation (A2-19) still holds.

For more complex fluid geometries than we have considered here, in general $\partial \mathcal{E} / \partial t \neq 0$ and magnetic fields will be created such that they will be amplified by the fluid motions to reach a large enough value to cushion them at the boundary (Schatzman 1970, Puget, to be published). When the magnetic field plays a dominant role, the condition of equipartition between the energy of the field produced and the energy going into heating the plasma leads to the relation

$$\frac{1}{2}(0.27 M_a c^2) = M_\lambda v_f^2 \quad (\text{A2-20})$$

which gives a much smaller value for M_a than equation (A2-19). Thus, most of the annihilations will occur in interactions when the magnetic field does not play a dominant role.

We now consider the transfer of energy from the annihilation into macroscopic fluid motions. Electrons in the boundary region are heated at a rate

$$(dE_e/dt) = (0.27 m_p c^2 v_f / 0.27 c) \tau_E^{-1} \quad (\text{A2-21})$$

as obtained from equation (A2-19) where τ_E is given by equation (A2-13).

Assuming the emulsion size d scales like λ_Y (see main paper and Omnes references) so that v_f scales like $d \lambda_Y / dt$.

The γ -ray mean-free-path

$$\lambda_Y = (n \sigma_Y)^{-1} \approx 1.6 \times 10^{31} (1+z)^{-3} \text{ cm} \quad (\text{A2-22})$$

It then follows from equations (A2-13), (A2-21) and (A2-22) that

$$(dE_e/dt)_X \simeq 9.1 \times 10^{-12} (1+z)^{5/2} \text{ eV/s} \quad (\text{A2-23})$$

The energy loss rate for cooling of electrons by interactions with the blackbody radiation is given by

$$\begin{aligned} (dE_e/dt)_{bb} &\simeq 4.8/3 \sigma_T c (E_e/m_e c^2)^2 \epsilon \\ &\simeq 2.7 \times 10^{-20} (1+z)^4 E_e \text{ eV/s} \end{aligned} \quad (\text{A2-24})$$

Weymann (1965).

It follows from equations (A2-23) and (A2-24), it follows that antimatter annihilation will heat up the electrons in the cosmic plasma at the boundary regions to an equilibrium energy given by

$$E_{eq} \simeq 3.4 \times 10^8 (1+z)^{-3/2} \text{ eV} \quad (\text{A2-25})$$

At this electron energy, energy is being fed through the plasma in a characteristic time obtained from equation (A2-19)

$$\tau_c = m_p v_f c (dE_e/dt)_{bb}^{-1} \quad (\text{A2-26})$$

We also note the other condition on the heating of the plasma electrons, viz., that they can only be heated to a maximum energy by the X-rays as given by equation (A2-8). The allowed energy range for the plasma electrons as given by the restrictions (A2-8) and (A2-25) is shown in figure 5 as a function of redshift. It follows from these restrictions, as shown in figure 5 that cooling by the blackbody radiation is unimportant for redshifts $\leq \sim 600$ because in this redshift range, electrons cannot be heated to E_{eq} as given by equation (A2-25).

The hot gas of electrons transmits its energy to the protons within a time τ_p given by (Spitzer 1962)

$$\tau_p = \frac{m_p^2 W_a^3}{32\pi e^4 n \ln \Lambda G(W_e/W_p)} \quad (\text{A2-27})$$

$$\simeq 1.1 \times 10^{25} (1+z)^{-21/4} \text{ s}$$

where w_e is the velocity of the hot electrons and $\ln \Lambda$ and $G(w_e/w_p)$ are the same functions as in (A2-6). It follows from equation (A2-27) that $\tau_p \leq 2 \times 10^{10}$ s for $(1+z) \geq \sim 600$.

The hot gas can expand almost freely within a dynamical time scale τ_{dyn} given by

$$\tau_{\text{dyn}} \simeq \lambda_X / v_p \quad (\text{A2-28})$$

where v_p is the thermal velocity of the hot protons in equilibrium with the hot electron gas. If $\tau_p < \tau_c$ and $\tau_p < \tau_{\text{dyn}}$, condition which is fulfilled for all $z \geq 600$, then $E_p \simeq E_e$ and

$$v_p = (2E_e/m_p)^{1/2} \simeq 2.6 \times 10^{10} (1+z)^{-3/4} \quad (\text{A2-29})$$

The dynamical expansion of the hot gas produces macroscopic fluid motion in the directions away from the boundary. Thus, a fraction $F \equiv \tau_{\text{dyn}}/\tau_c$ of the energy released in the form of relativistic electrons in the annihilation is transformed into macroscopic fluid motion rather than being cooled by the blackbody radiation field. From equations (A2-24), (A2-26), (A2-28) and (A2-29), we then obtain an expression for the dynamic efficiency F

$$F \simeq 7 \times 10^4 (1+z)^{-7/4} \quad \text{for } (1+z) \geq \sim 600 \quad (\text{A2-30})$$

$$\text{and} \quad F \simeq 1 \quad \text{for } (1+z) \leq \sim 600 \quad (\text{A2-31})$$

when cooling by blackbody radiation is no longer important.

Appendix 3: Neutralization Period of the Cosmic Plasma.

The neutralization of the cosmic plasma is slower in the baryon-symmetric cosmology than in the normal "big-bang" cosmology, because the annihilation products keep the plasma ionized at a higher level than would be expected from purely thermal considerations. A detailed solution of the neutralization problem for the normal "big-bang" cosmology has been given by Peebles (1968). The equation he given for the electron density is

$$dn_e/dt = C(n_H, T) \{ \alpha_c n_e^2 - \beta_c n_H \exp -(B_1 - B_2)/kT \} \quad (A3-1)$$

where B_n is the binding energy for a hydrogen atom with its electron in an orbit of quantum number n and n_H is the density of hydrogen atoms in the ground state. The α_c and β_c coefficients are functions of temperature T .

In order to investigate the effect of the annihilation products on the neutralization of the cosmic plasma, we have considered the behavior of these products. The neutrinos which carry roughly half of the annihilation energy have no ionizing effect. The γ -rays lose their energy by pair production and Compton interactions with an effective cross section $\approx 2 \times 10^{-26} \text{ cm}^2$ (See, e.g., Stecker 1971) with the secondary electrons having an energy of the same order of magnitude as that of the parent γ -rays. γ -rays are also produced by the annihilation of electrons and positrons after they have been slowed down (see also Stecker 1971). The electrons and positrons resulting from matter antimatter annihilation, of course, produce X-rays as we have discussed in appendix 2.

The X-rays can themselves undergo two interaction processes, viz., photoionization and Compton interactions. The photoionization cross section depends strongly on E_x and is given by

$$\sigma_X = \sigma_T (2/2\alpha^4) (m_e c^2/E_x)^{7/2} \quad (A3-2)$$

where α here is the fine structure constant. (see, e.g., Heitler 1954).

The X-rays are very efficient ionizing agents and tend to slow down the neutralization of the plasma. At the beginning of their life, the most energetic X-rays are degraded by Compton interactions with free electrons. This process, however, becomes unimportant when the energy of the X-rays falls below a few keV, at which point photoionization becomes important if only 1% of the hydrogen is neutral.

The number of ionizations per annihilation is thus given by

$$k_i \approx 0.5 (2m_p c^2 / 32 \text{ eV}) (1-x) \quad (\text{A3-3})$$

(where x is the fraction of hydrogen in an ionized state) because one ionization corresponds to the ultimate loss of 32 eV by a fast electron.

The equation for ionization equilibrium then becomes

$$dn_e / dt = \alpha_c n_e^2 C(n_H, T) - \Psi_v k_i = 0 \quad (\text{A3-4})$$

where Ψ_v is the annihilation rate per unit volume.

Equation (A3-4) reduces to

$$C(T, x) x^2 = 6.75 \times 10^{-6} (1-x) (1+z) \quad (\text{A3-5})$$

if we adopt the value given by equation (9) of the main text as a lower limit on Ψ_v at $z \sim 10^3$ (see main text for discussion).

The solution to equation (A3-5) is shown in table A3-1. It follows from this table that "total" neutralization takes place later in the baryon-symmetric cosmology than in the normal all-matter cosmology. Several remarks are in order concerning this result. For $T < 10^3 \text{ K}$, $x \propto T^{\frac{1}{2}}$. However, this value of x is an average; stronger ionization will occur in the vicinity of the boundary regions. Another important point is that the annihilation rate decreases rapidly with z . As we show in the main text, part of the annihilation energy may be stored in large scale turbulence for $500 < z < 10^3$. Part of this kinetic energy is therm-

alized later when the recombination rate (proportional to n^2) is much smaller. Thus, we should consider the results of table A3-1 to represent lower limits on the value of x .

The sound velocity for a plasma coupled to the blackbody radiation field is

$$u_{pl} = \left(\frac{5kT}{3m_p} \right)^{1/2} \left[1 + \frac{2n_\gamma^2}{5n_p(n_p + 2n_\gamma)} \right]^{1/2} \quad (A3-6)$$

where n_γ is the blackbody photon density and n_p is the proton density.

The sound velocity for a neutral gas at temperature T is

$$u_n = (5kT/3m_p)^{1/2} \approx v_t \quad (A3-7)$$

The ratio

$$u_n/u_{pl} \sim (n_p/n_\gamma)^{1/2} \sim 10^{-4} \quad (A3-8)$$

Thus, the sound velocity of the cosmic gas drops by about four orders of magnitude by the end of the neutralization period and the fluid velocities considered in part III of the main text will then become supersonic (see figure 2). The transition takes place when the mean-free-path of the photons becomes larger than the characteristic fluid dimension d (see, e.g., Ozernoi and Chernin 1968 for further discussion). The mean free-path of the thermal photons is

$$\lambda_{th} \equiv \lambda_X/x \quad (A3-9)$$

where λ_X is given by equation (A2-10). The X-rays, as shown in appendix 2, have a lifetime much longer than λ_X/c . If this lifetime is \geq the hydrodynamic time $\tau_h = d/v_f$, they will contribute to maintaining a high sound velocity (The effect of high-energy photons on the sound velocity has been studied by Montmerle 1971). This condition for the high sound velocity is fulfilled for $z \geq \sim 500$. Figure 3 shows that the mean-free-path for the thermal photons becomes larger than d for $z \leq \sim 600$. We will thus consider neutralization (corresponding to the transition from u_{pl} to u_n to occur for $z_n \approx 5 \pm 1 \times 10^2$ (keeping in mind that we may have somewhat underestimated the value of $x(z)$).

TABLE 3A-1 . NEUTRALIZATION OF THE COSMIC PLASMA

Z	Peebles(1968)		This Work	
	x	C(T,x)	x	C(T,x)
1660	0.92	1.8×10^{-4}	0.96	3.6×10^{-4}
1480	0.40	5.9×10^{-4}	0.84	2.2×10^{-3}
1300	0.072	2.7×10^{-3}	0.64	7×10^{-3}
1100	9.8×10^{-3}	2×10^{-2}	0.38	3.2×10^{-2}
925	9.2×10^{-4}	0.25	0.14	0.3
740	1.23×10^{-4}	0.96	0.068	1
550	5.3×10^{-5}	1	0.06	1
370			0.049	

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FIGURE CAPTIONS

Figure 1. The growth of the matter and antimatter regions as a function of cosmic temperature ($T = 2.7K(1+z)$).

Figure 2. Various velocities discussed in the text given as a function of redshift. (c) speed of light, (u_{pl}) speed of sound in the cosmic plasma, (u_n) speed of sound in the neutralized gas, $v_{f,max}$ as given in equation (12), v_f as given in equation (10) which gives the lower limit on the fluid velocity at z_n ; v_t is the thermal velocity and $v_{max}(1)$ is given by equation (1).

Figure 3. Range of emulsion size d as a function of redshift as discussed in the text.

Figure 4. Various annihilation rates discussed in the text as a function of redshift.

Figure 5. Allowed range of electron energy as determined by equations (A2-8) and (A2-25).









